Space-Time Transmit Diversity Combined with Frequency-domain Equalization for Single-carrier Transmission

Kazuaki TAKEDA[+], Takeshi ITAGAKI[+], and Fumiyuki ADACHI[++]
Dept. of Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University
05 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan
E-mail: [+]{takeda, itagaki}@mobile.ecei.tohoku.ac.jp, [++]adachi@ecei.tohoku.ac.jp

Abstract

In a frequency-selective fading channel, the transmission performance of single-carrier (SC) transmission significantly degrades due to severe inter-symbol-interference (ISI). In this paper, the joint use of space-time transmit diversity (STTD), receive antenna diversity and frequency-domain minimum mean square error (MMSE) equalization in SC transmission is studied. Space-time encoding and decoding for frequency-domain MMSE equalization is proposed. The bit error rate (BER) performance of SC transmission is evaluated by computer simulation. It is found that joint use of STTD, receive antenna diversity and frequency-domain MMSE equalization can significantly improve the BER performance in a severe frequency-selective fading channel.

Keywords

Single carrier transmission, space-time transmit diversity, frequency-domain equalization, frequency-selective fading

1. Introduction

Wireless channel is composed of many propagation paths with different time delays, producing frequency-selective multipath fading [1]. In a frequency-selective fading channel, the bit error rate (BER) performance of single-carrier (SC) transmission significantly degrades due to severe inter-symbol-inference (ISI). Direct-sequence code division multiple access (DS-CDMA) can exploit the channel frequency-selectivity by the use of rake receiver that resolves the propagation paths having different time delays and coherently combines them to achieve the path diversity effect [2]. Wideband DS-CDMA has been adopted as a wireless access technique in the 3rd generation mobile communications systems, known as IMT-2000 systems, for data transmissions of up to a few Mbps [3]. However, in the case of broadband wireless data transmissions more than a few Mbps using DS-CDMA, the transmission performance may significantly degrade due to large inter-path interference (IPI) even if coherent rake combining is used.

Recently, multi-carrier code division multiple access (MC-CDMA) has been attracting much attention for broadband wireless data transmissions in a severe frequency-selective channel [4~6]. In MC-CDMA, the frequency diversity effect is attained by one-tap frequency-domain equalization, resulting in a better BER performance than DS-CDMA using coherent rake combining [7]. However, the MC-CDMA has a problem of large peak-to-average power ratio (PAPR) and thus, a linear transmit power amplifier with a large peak power is required. Quite recently, SC transmission using one-tap frequency-domain equalization has been gaining an increasing popularity [8]. SC transmission has an advantage that the problem of high PAPR can be avoided and the computational complexity of frequency-domain equalization does not depend on the degree of channel frequency-selectivity.

Transmit/receive antenna diversity is a well-known effective technique to improve the transmission performance [9]. In this paper, we apply two-antenna space-time transmit diversity (STTD) [10] to further improve the BER performance of SC transmission with frequency-domain equalization. Space-time encoding and decoding combined with frequency-domain equalization is proposed. Remainder of this paper is organized as follows. Section 2 presents space-time encoding and decoding combined with frequency-domain minimum mean square error (MMSE) equalization. In Section 3, the achievable BER performance in a frequency-selective Rayleigh fading channel is evaluated by computer simulation. The BER performance achievable with STTD combined with frequency-domain MMSE equalization is compared with that of simple delay transmit diversity (DTD) [11]. Section 4 offers some conclusions and future work.

2. STTD Combined with Frequency-domain Equalization

2.1 Space-time encoding suitable for frequency-domain MMSE equalization

Figure 1 illustrates the transmitter and receiver structures for SC transmission with STTD combined with frequency-domain equalization. Throughout the paper, a discrete time representation of the signal is used. The data symbol sequence to be transmitted is transformed into a sequence of data blocks, each with N_c symbols. N_c-data symbol sequence of the q-th block is denoted by $\{d(t); t = qN_c \sim (q+1)N_c - 1\}$. The SC signal sample sequence $\{s(t); t = qN_c \sim (q+1)N_c - 1\}$ of the q-th block is expressed using the equivalent lowpass representation as

$$s(t) = \sqrt{2E_s / T}\, d(t), \quad (1)$$

where E_s is the transmit signal energy per symbol and T is the symbol length.

We extend Alamouti's STTD encoding [10] to the SC transmission using frequency-domain equalization. The signal blocks $\{s_e(t)\}$ and $\{s_o(t)\}$ which represent the even (q=2u) and odd (q=2u+1) signal blocks, respectively, are transmitted simultaneously after insertion of guard interval (GI) from two transmit antennas during the time interval of two consecutive (even and odd) data blocks. Let the subcarrier components of the even (q=2u) and odd (q=2u+1) signal blocks be denoted by $\{S_e(k)\}$ and $\{S_o(k)\}$, respectively (note that although SC transmission does not use subcarriers for modulation, the terminology "subcarrier" is used for explanation purpose only). They are given by

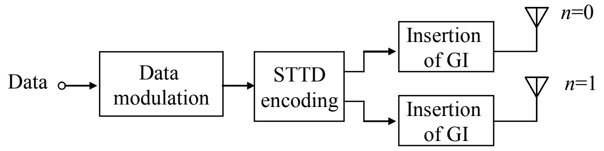
$$\begin{cases} S_e(k) = \sum_{t=0}^{N_c-1} s_e(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \\ S_o(k) = \sum_{t=0}^{N_c-1} s_o(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \end{cases} \quad (2)$$

for k=0~N_c-1. The STTD encoding using $\{S_e(k)\}$ and $\{S_o(k)\}$ is carried out subcarrier-by-subcarrier as shown in Table 1. This subcarrier-by-subcarrier STTD encoding allows decoding to be combined with frequency-domain equalization (this is described in Sect 2.2).

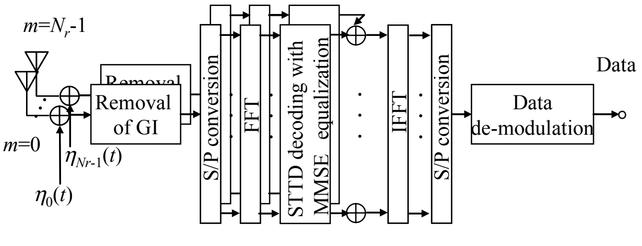
The above STTD encoding requires the N_c-point fast Fourier transform (FFT) and inverse FFT (IFFT) operations to obtain $\{S_e(k)\}$ and $\{S_o(k)\}$ and transform them back to time-domain signals. Below, an equivalent time-domain STTD encoding that requires no FFT and IFFT operations is presented. Applying N_c-point IFFT to $\{S_e^*(k)\}$ and $\{S_o^*(k)\}$, we obtain

$$\begin{cases} \frac{1}{N_c}\sum_{k=0}^{N_c-1} S_e^*(k)\exp\left(j2\pi t\frac{k}{N_c}\right) = s_e^*(N_c-t) \\ \frac{1}{N_c}\sum_{k=0}^{N_c-1} S_o^*(k)\exp\left(j2\pi t\frac{k}{N_c}\right) = s_o^*(N_c-t) \end{cases} \quad (3)$$

for t=0~N_c-1, where $(\ )^*$ denotes the complex conjugate. Hence, STTD encoding of Table 1 can be replaced by time-domain STTD encoding shown in Table 2. STTD encoding process is shown in Fig.2. The last N_g symbols in each STTD encoded signal block are copied and inserted into the beginning of each block as the GI. The GI-inserted signal sample streams are simultaneously transmitted from two antennas over a frequency-selective fading channel.



(a) Transmitter



(b) Receiver

Fig.1 Transmitter and receiver with joint STTD and frequency-domain equalization.

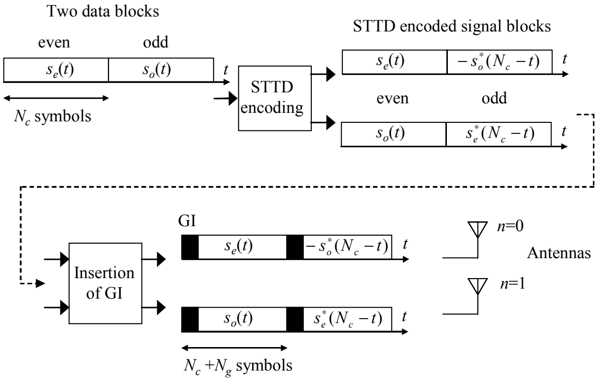


Fig.2 STTD encoding process for transmission from two transmit antennas.

Table 1 STTD encoding

Time (in block)	Antenna index n	
	0	1
Even (q=2u)	$S_e(k)$	$S_o(k)$
Odd (q=2u+1)	$-S_o^*(k)$	$S_e^*(k)$

Table 2 Equivalent time-domain STTD encoding

Time (in block)	Antenna index n	
	0	1
Even (q=2u)	$s_e(t)$	$s_o(t)$
Odd (q=2u+1)	$-s_o^*(N_c-t)$	$s_e^*(N_c-t)$

2.2 Joint STTD decoding and frequency-domain MMSE equalization

The STTD encoded signal sample streams transmitted from the two antennas are assumed to be received by N_r antennas at a receiver. The propagation channel is assumed to be a symbol-spaced L-path frequency-selective fading channel, each path being subjected to independent fading. Block fading, where the path gains stay constant over two (even and odd)-block interval, has been assumed. After removal of GI, the even and odd block signal sequences received on the m-th antenna are decomposed by N_c-point FFT into N_c subcarrier components $\{R_{e,m}(k);\ k$=0~N_c-1$\}$ and $\{R_{o,m}(k);\ k$=0~N_c-1$\}$, respectively. $R_{e,m}(k)$ and $R_{o,m}(k)$ can be written as

$$\begin{cases} R_{e,m}(k) = H_{0,m}(k)S_e(k) + H_{1,m}(k)S_o(k) + N_{e,m}(k) \\ R_{o,m}(k) = -H_{0,m}(k)S_o^*(k) + H_{1,m}(k)S_e^*(k) + N_{o,m}(k) \end{cases}, \quad (4)$$

where $\{H_{0,m}(k)\}$ and $\{H_{1,m}(k)\}$ represent respectively the N_c-point Fourier transforms of the channel gains associated with the 0-th and the 1st transmit antennas, and $\{N_{e,m}(k)\}$ and $\{N_{o,m}(k)\}$ respectively represent the Fourier transforms of noise processes. One-tap frequency-domain equalization is carried out jointly with STTD decoding and receive antenna diversity combining to obtain $\{\tilde{S}_e(k)\}$ and $\{\tilde{S}_o(k)\}$:

$$\begin{cases} \tilde{S}_e(k) = \sum\limits_{m=0}^{N_r-1}\left\{w_{0,m}^*(k)R_{e,m}(k)+w_{1,m}(k)R_{o,m}^*(k)\right\} \\ \tilde{S}_o(k) = \sum\limits_{m=0}^{N_r-1}\left\{w_{1,m}^*(k)R_{e,m}(k)-w_{0,m}(k)R_{o,m}^*(k)\right\} \end{cases} \qquad (5)$$

for k=0~N_c-1, where $w_{0,m}(k)$ and $w_{1,m}(k)$ are the STTD decoding weights. Direct application of decoding presented in [10] gives

$$\begin{cases} w_{0,m}^{(MRC)}(k) = H_{0,m}(k) \\ w_{1,m}^{(MRC)}(k) = H_{1,m}(k) \end{cases}, \qquad (6)$$

which are the maximal-ratio combining (MRC) weights. Another solution is that the weights are chosen so that the mean square error (MSE) between $\tilde{S}_e(k)$ and $S_e(k)$ and that between $\tilde{S}_o(k)$ and $S_o(k)$ are jointly minimized. Following [6], we can obtain

$$\begin{cases} w_{0,m}^{(MMSE)}(k) = \dfrac{H_{0,m}(k)}{\sum\limits_{n=0}^{1}\sum\limits_{m=0}^{N_r-1}|H_{n,m}(k)|^2+\left(\dfrac{1}{2}\dfrac{E_s}{N_0}\right)^{-1}} \\ w_{1,m}^{(MMSE)}(k) = \dfrac{H_{1,m}(k)}{\sum\limits_{n=0}^{1}\sum\limits_{m=0}^{N_r-1}|H_{n,m}(k)|^2+\left(\dfrac{1}{2}\dfrac{E_s}{N_0}\right)^{-1}} \end{cases}, \qquad (7)$$

where E_s/N_0 is the average received signal energy per symbol-to-AWGN power spectrum density ratio per receive antenna. Removing the second term in the denominator of Eq. (7) leads to zero-forcing (ZF) weights:

$$\begin{cases} w_{0,m}^{(ZF)}(k) = \dfrac{H_{0,m}(k)}{\sum\limits_{n=0}^{1}\sum\limits_{m=0}^{N_r-1}|H_{n,m}(k)|^2} \\ w_{1,m}^{(ZF)}(k) = \dfrac{H_{1,m}(k)}{\sum\limits_{n=0}^{1}\sum\limits_{m=0}^{N_r-1}|H_{n,m}(k)|^2} \end{cases} \qquad (8)$$

N_c-point IFFT is applied to $\{\tilde{S}_e(k)\}$ and $\{\tilde{S}_o(k)\}$ to obtain the time-domain soft decision sample sequences used for the data demodulation.

3. Computer simulation

The average BER performance of SC transmission with joint STTD and frequency-domain equalization is evaluated by computer simulation. The simulation parameters are given in Table 3. Binary phase shift keying (BPSK) data modulation, N_c=256, N_g=32, and a symbol-spaced L-path frequency-selective block Rayleigh fading having an exponential power delay profile with decay factor α dB are assumed. Ideal sampling timing and ideal channel estimation are also assumed at the receiver.

Table 3 Simulation parameters

Transmitter	Modulation	BPSK
	Number of FFT points	N_c=256
	GI	N_g=32(symbols)
	Transmit diversity	STTD
Channel	Fading	Frequency -selective block Rayleigh fading
	Power delay profile	L=16-path exponential power delay profile
		Decay factor α=0,2,8,∞(dB)
Receiver	Number of receive antennas	N_r=1,2,4
	Frequency-domain Equalization	MMSE, MRC, ZF
	Channel estimation	Ideal

3.1 BER performance evaluation

How STTD combined with frequency-domain MRC, MMSE or ZF equalization improves the average BER performance is discussed. Figure 4 plots the average BER performance with the decay factor α dB as a parameter as a function of the average signal energy per information bit-to-AWGN power spectrum density ratio E_b/N_0, which is given by $E_b/N_0=(1+N_g/N_c)(E_s/N_0)$. It is clearly seen that MMSE equalization gives the better BER performance than MRC and ZF equalization. Using MRC, BER floors are seen when α=0, 2 and 8dB due to the large ISI produced by the enhanced frequency-selectivity. MMSE equalization can suppress the noise enhancement while almost restoring the frequency non-selective channel. Hence, irrespective of the degree of channel frequency-selectivity, the BER performance with MMSE equalization is always better than ZF equalization. Hence, in the following, we use the MMSE equalization only.

The BER performances with STTD and without STTD are compared in Fig. 5 with the decay factor α dB as a parameter. Since frequency-domain MMSE equalization can achieve frequency diversity effect by taking advantage of frequency-selective fading, α=0 dB gives better BER performance than the case of α=8 dB. Joint STTD and frequency-domain MMSE equalization gives further improved BER performance. An STTD gain of 3.2dB at BER=10^{-4} is obtained when α=0 dB.

An additional use of receive antenna diversity can further improve the BER performance. Figure 6 plots the average BER performance as a function of the average E_b/N_0 with α and the number N_r of receive antennas as parameters. The use of receive antenna diversity is always beneficial irrespective of the degree of channel frequency-selectivity. When α=0 dB and N_r=2, a combined STTD/receive diversity gain of 4.4dB is obtained at BER=10^{-4} compared with N_r=1. When N_r=4, a combined diversity gain of as much as 8 dB is obtained.

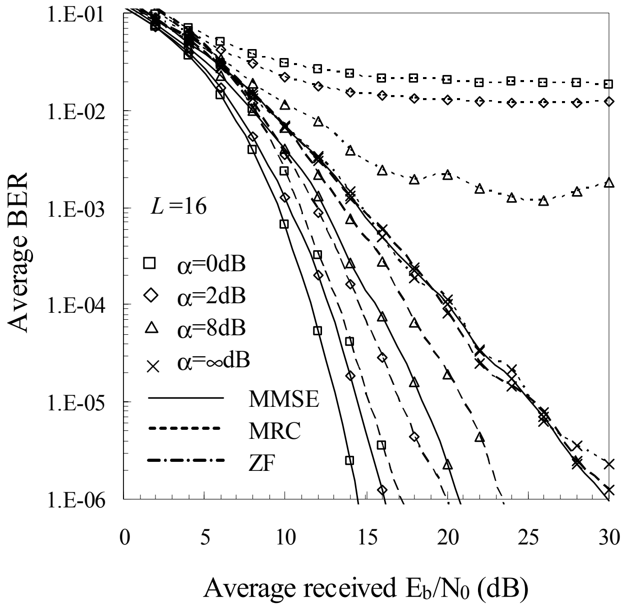


Fig.4 Simulated BER performances with joint STTD and MMSE, MRC and ZF. No antenna diversity (N_r=1).

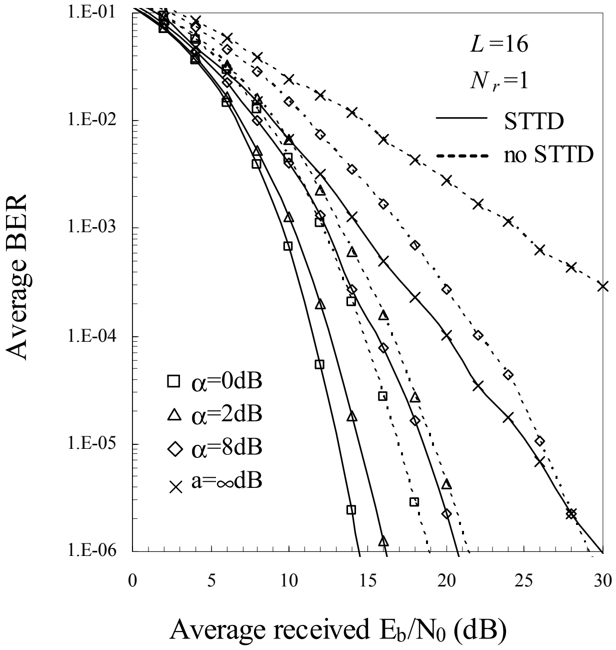


Fig.5 The BER performance with joint STTD and MMSE equalization.

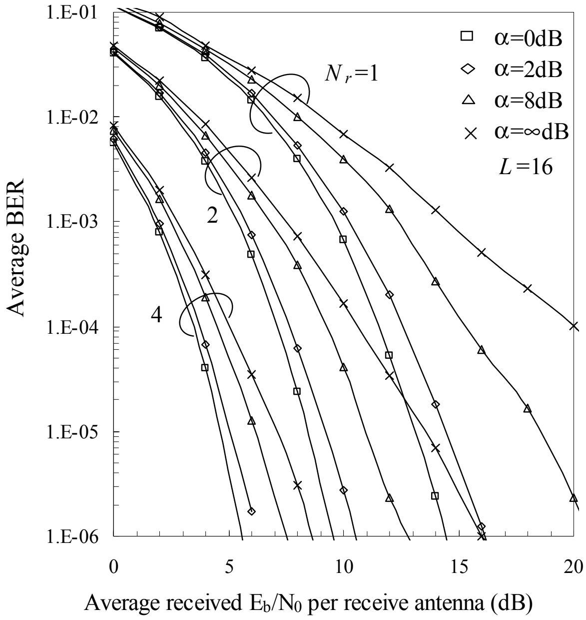


Fig 6. Effect of joint STTD and receive antenna diversity.

3.2 Comparison with delay transmit diversity (DTD)

Another simple transmit diversity is the so called delay transmit diversity (DTD) [11]. We compare the BER performances achievable by STTD and DTD. Figure 7 compares the BER performances achievable by STTD and DTD with the decay factor α dB as a parameter. For comparison, the BER performance for no transmit diversity is also plotted. As the channel frequency-selectivity increases (α decreases), all the BER performances of STTD, DTD and no transmit diversity improve. When α=8 dB, the channel frequency-selectivity is strong and hence, the BER performance with DTD improves. An additional gain of 2.5dB at BER=10^{-4}, however, is attained by STTD compared to DTD, since STTD doubles the equivalent number of receive antenna branches. When α=0 dB, on the other hand, the DTD gain is only 0.4dB because the channel frequency-selectivity is already strong enough. However, a STTD gain of as much as 3.2dB is still obtained compared to no transmit diversity.

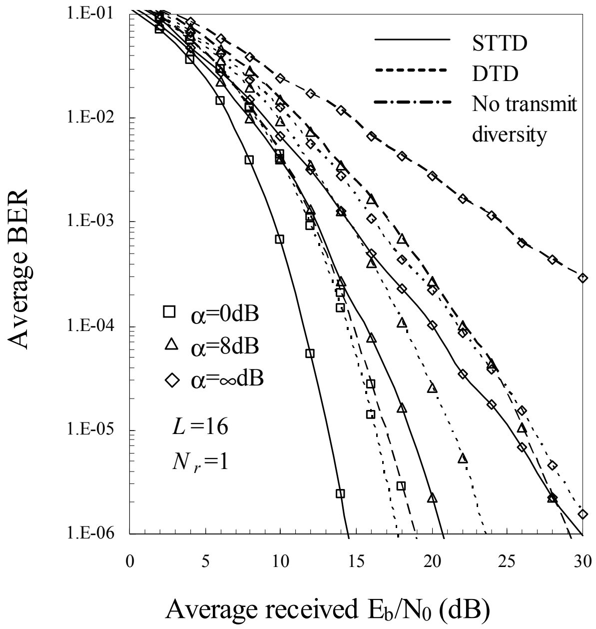


Fig.7 BER performance comparison between STTD and DTD.

4. Conclusion

In this paper, STTD combined with frequency-domain equalization was presented for SC transmission in a frequency-selective fading channel and the BER performance was evaluated by computer simulation. The STTD encoding suitable for frequency-domain equalization was proposed, in which Alamouti's STTD encoding [10] is applied to each subcarrier component (obtained by FFT) of the transmitting signal sequence. The direct application of Alamouti's STTD encoding requires FFT and IFFT operations. In this paper, the STTD encoding that does not require FFT and IFFT was proposed.

Performance comparison of STTD and DTD has shown that STTD combined with frequency-domain MMSE equalization always gives a better BER performance than DTD irrespective of the degree of the channel frequency-selectivity. This is because STTD with frequency-domain MMSE equalization is equivalent to receive antenna diversity combining with two-branch MRC while DTD expects the increased frequency diversity effect by increasing the equivalent number of propagation paths and therefore, DTD gain becomes smaller as the propagation channel frequency-selectivity is already strong enough.

In this paper, ideal channel estimation and block fading, where the channel gains stay constant over two-signal block interval, were assumed. The BER performance using practical channel estimation in a fast fading environment is left for future study.

Reference

[1] W. C. Jakes, Jr., Ed., *Microwave mobile communications*, Wiley, New York, 1974.
[2] J. G. Proakis, *Digital communications*, 3rd ed., McGraw-Hill, 1995.
[3] F. Adachi, M. Sawahashi, and H. Suda, "Wideband DS-CDMA for next generation mobile communications systems," IEEE Commun. Mag., Vol. 36, pp. 56-69, Sept. 1998.
[4] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Commun. Mag., Vol. 35, pp. 126-144, Dec. 1997.
[5] H. Atarashi, S.Abeta and M. Sawahashi, "Variable spreading factor-orthogonal frequency and code division multiplexing (VSF-OFCDM) for broadband packet wireless access," IEICE Trans. Commun., Vol. E86-B, No.1, pp. 291-299, Jan. 2003.
[6] F. Adachi and T. Sao, "Joint antenna diversity and frequency-domain equalization for multi-rate MC-CDMA," IEICE Trans. Commun., to appear.
[7] T. Sao and F. Adachi, "Comparative study of various frequency equalization techniques for dounlink of a wireless OFDM-CDMA system," IEICE Trans. Commun., Vol. E86-B, pp.352-364, Jan. 2003.
[8] D. Falconer, et al., "Frequency domain equalization for single-carrier broadband wireless systems," IEEE Commun., Mag., Vol. 40, pp. 58-66, April 2002.
[9] R. T. Derryberry, et al., "Transmit diversity in 3G CDMA systems," IEEE Commun. Mag., pp.68-75, April 2002.
[10] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," IEEE J. Sel. Areas Commun., Vol.16, No.8, pp.1451-1458, Oct. 1998.
[11] J. H. Winters, "Diversity gain of transmit diversity in wireless systems with Rayleigh fading," IEEE Trans. Veh. Technol., Vol. 47, pp.119-123, Feb. 1998.